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Viscoelastic Properties of Selected Pvb Interlayers for Laminated Glass

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Abstract:

In contemporary architecture, laminated glass panes are widely used for structural elements loaded perpendicularly to its surface such as floors, roofing, facades etc. It is sought-after for its transparency and smooth reflective surface. In this case, it is advisable to consider the interaction of the individual glass panes in the cross-section. A conservative approach, that does not take into account the shear interaction of glass panes, is uneconomical. Various commercial products based on PVB (polyvinyl butyral), EVA (ethylene vinyl acetate), ionomer, or thermoplastic polyurethane (TPU) are used. Stiffness of polymers depends on temperature and duration of a load. Interlayers exhibit the viscoelastic properties and temperature dependence is usually described by the generalized Maxwell model and WLF model (Williams-Landel-Ferry). Parameters of these models are most effectively determined by Dynamic Mechanical Thermal Analysis (DMTA), where the material is cyclically loaded at different frequencies and temperatures. Two types of PVB interlayers (Trosifol® Extra Strong and Trosifol® BG-R-20) were investigated using DMTA in the research carried out at Klokner Institute, CTU in Prague. In addition, experimental quasi-static loading tests were performed in shear at various loading rates and temperatures. The testing arrangement was a single lap shear test in both cases. The experimental stress-strain diagrams from static tests were compared with the theoretical diagrams derived from material parameters based on DMTA testing. Although both materials are PVB-based, shear stiffness and temperature dependence are considerably different due to additives added to the PVB feedstock. These differences in material behavior are important because the actual material properties have to be taken into account in the design of laminated glass structure.

Keywords: Laminated Glass; Polymeric Interlayer; Shear-Coupling; Maxwell Model; WLF Model; DMTA.

DOI:

1. INTRODUCTION

Laminated glass, which is composed of two or more glass panes bonded together by transparent polymeric interlayers, is the subject of a current researches [1, 2]. One of the reasons is the creation of new European standards, i.e. Eurocodes, for the design of load-bearing glass structures. For a reliable and economical design of laminated glass panels, the knowledge of interlayer´s mechanical properties used in these structures is fundamental because of the physical description of the shear-coupling of the layers in laminated glass. The most important property affecting the stress-state and vertical deflections of laminated panels perpendicularly loaded, is the shear stiffness of the interlayer. This quantity is time and temperature dependent. When shear stiffness is infinite, all glass panes in the laminated panel are fully shear coupled. On the other hand, when the shear stiffness is zero, glass panes do not interact and carry the load separately. In practice, the situation is somewhere between these border cases and depends on the load type and the environmental conditions.

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The aim of this paper is to provide parameters for a viscoelastic description of interlayer made of polyvinyl butyral, trade-mark Trosifol® Extra Strong, to be able to predict its shear stiffness in time and temperature domain. The PVB interlayer Trosifol® BG-R-20 has been already investigated and published in detail [3].

2. VISCOELASTICITY of POLYMERIC INTERLAYERS

The viscoelastic material is described for the uniaxial shear stress by Boltzmann's principle of superposition [4, 5].

$$\tau(t) \ = \ \int_{-\infty}^{t} G(t-s)\,\dot{\gamma}(s)\,ds \ , \qquad (2.1)$$

where $\tau(t)$ is the shear stress in time, $\gamma(s)$ refers to the engineering shear strain rate at the instant time s, and G(t) is the relaxation function. This function is usually considered in the form of the generalized Maxwell model [3, 4] according to the following equation

$$G(t) = \ G_\infty + \ \sum_{i=1}^{n} G_i \exp(-\,t/\tau_i) \ , \qquad (2.2)$$

where G_∞ is the equilibrium shear stiffness modulus, G_i expresses the shear stiffness corresponding to the relaxation time τ_i of the i-th Maxwell element, and n is the number of Maxwell elements in the Maxwell model. The equations (1) and (2) describe the response of the viscoelastic material depending on the load duration and its history.

The dependence of the viscoelastic material on a temperature can be expressed by the WLF model [6]. than In case of the generalized Maxwell model of the thermo-rheologically simple material, each relaxation time τ_i (T_0) determined for the reference temperature T_0 is substituted by $\tau_i\,(T)=\alpha_T\tau_i\,(T_0)$, where α_T is the shift factor determined from the following equation with non-dimensional constants C_1, C_2 as

$$\log \alpha_T = \ -C_1(T-T_0)/(C_2+T-T_0) \ . \qquad (2.3)$$

The most progressive testing of a viscoelastic material is by the Dynamic Mechanical Thermal Analysis (DMTA) [1, 2]. The sample is loaded by cyclic deformation $\gamma(t)=\gamma_0 \sin\omega t$. If this term is substituted in Boltzmann's principle of superposition (1), the integration leads to the trigonometric form of complex modulus G^* with its real part (storage modulus G') and imaginary part (loss modulus G") as

$$\tau(t) = \gamma_o\,[G'\sin\omega t \ + G''\cos\omega t] = \tau_o \sin(\omega t+\delta) \ . \qquad (2.4)$$

The stress-strain relationships in Fig. 1 show their phase shift δ and the viscoelastic loop in case of cyclic loading.

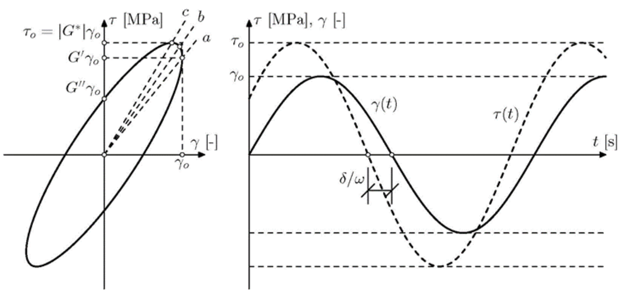

Figure 1. Cyclic loading of viscoelastic material: stress-strain diagram and phase-shift between engineering strain and stress functions in time

The DMTA analysis applies to the cyclic loading of a sample at different frequencies and temperatures. Then, several curves of complex modulus G^* are obtained in some frequency range depending on the possibilities of a testing system, see Fig. 2. The temperature effect by WLF model can be also interpreted as the time t in relaxation function G(t) is substituted by t/α(T). Therefore, there is a shift of the experimental curves equal to $\log \alpha_T$ on log-scaled axis of frequency. Parameters C_1 and C_2 of WLF model and master curve are obtained from the regression analysis minimizing the differences of the shifted curves. Then, the viscoelastic parameters of the Maxwell model fitting the constructed master curve can be determined.

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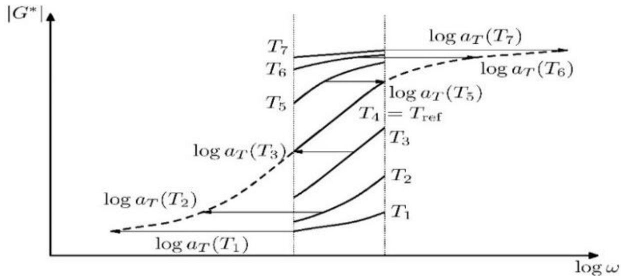

Figure 2. Horizontal shift of measured relations in DMTA analysis and the construction of the corresponding master curve (dashed)

3. EXPERIMENTAL INVESTIGATION

To find the viscoelastic parameters, DMTA tests of Trosifol® BG-R-20 specimens were performed at Klokner Institute CTU in Prague. The range of tested temperatures stated between -5 °C and +40 °C, and the range of testing frequencies stated between 0.05 Hz and 4.95 Hz. Based on these experiments, the generalized Maxwell model was constructed, and its parameters were evaluated. A technique for material parameters evaluation combined the linear regression and the Kuntsche method [7].

The shear test of polymeric interlayer for laminated glass was performed in the single lap arrangement as shown in Fig. 3. The shear area of the interlayer was 50 x 50 mm. The testing specimens were made of laminated glass by a milling cutter and water jet.

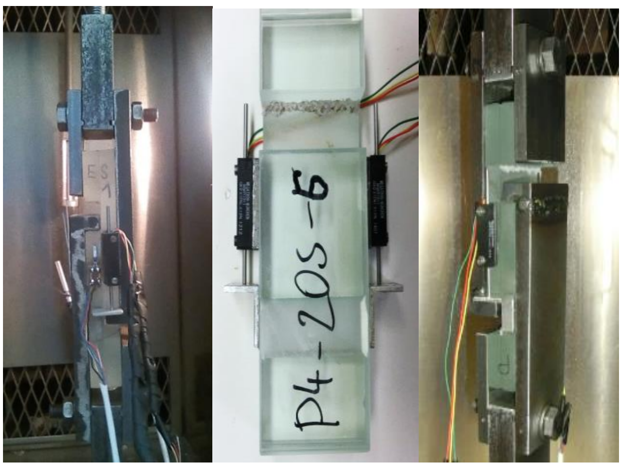

Figure 3. Test arrangement: a) arrangement in case of DMTA (testing specimen in climatic chamber), b) testing specimen of laminated glass with displacement transducers, c) arrangement in case of quasi-static test.

The shear strain γ was determined from the thickness of the interlayer measured microscopically and from the displacement of the glass panes measured by the displacement transducers MMR1011. The displacement measurement was conducted directly on the sample, see Fig. 3. The temperature of glass in DMTA was controlled by two sensors Pt100 glued on the sample surface (Fig. 3a). This temperature measurement showed to be very important. Force was measured by load cell HBM U9B 20 kN. The universal hydraulic testing system MTS with climatic chamber TIRA TEST T250/1 was utilized for DMTA analysis.

4. RESULTS

The DMTA results for the representative specimens of Trosifol® Extra Strong are presented in Fig. 4, where the storage modulus is plotted against frequency for each temperature step in the logarithmic scale. In the sense of regression analysis, parameters C_1 and C_2 of the WLF model and the appropriate master curve of Trosifol® Extra Strong for the reference temperature 20 °C were evaluated, see Fig. 5, where master curve of Trosifol® BG-R-20 is added for comparison. The shear stiffness modulus G in time, i.e., relaxation function for the temperature of 20 °C with its approximation from the literature [4], and the viscoelastic parameters of the fitted Maxwell model are presented in Fig. 6 and in Tab. 1, respectively.

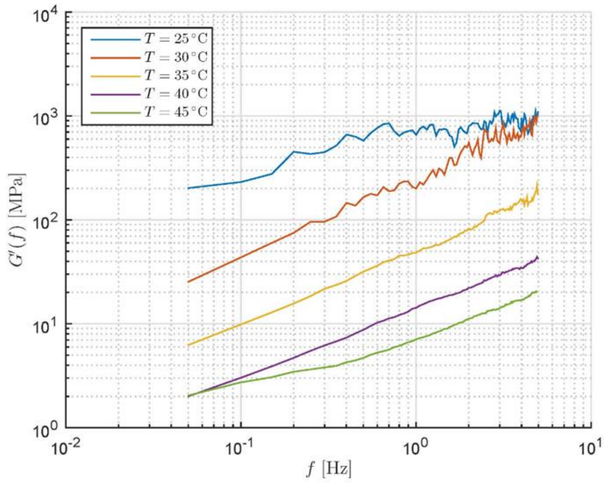

Figure 4. Measured storage modulus G' (f) of Trosifol® Extra Strong at different temperatures.

Corresponding Author E-mail: miroslav.vokac@cvut.cz

Acta Materialia Turcica

Volume 4, October 2020, Pages 37-42

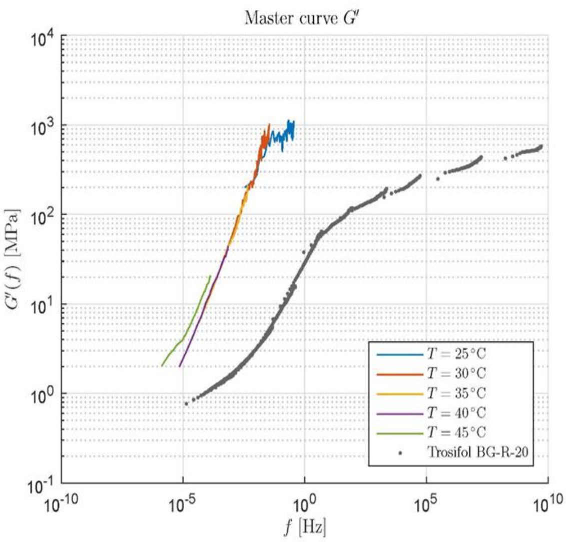

Figure 5. Constructed master curve of interlayer Trosifol® Extra Strong for the temperature 20 °C and comparison with previously tested Trosifol® BG-R-20.

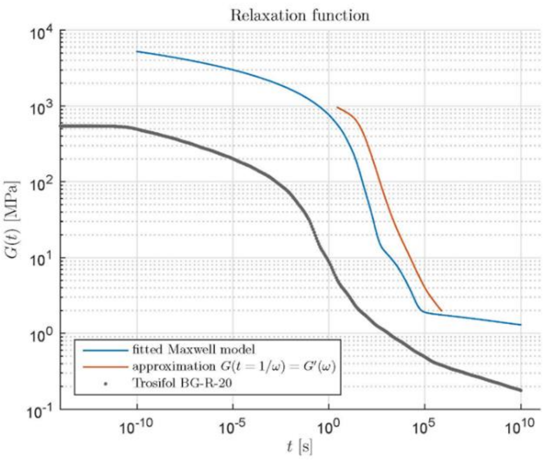

Figure 6. Fitted relaxation function of the interlayer Trosifol® Extra Strong for the reference temperature 20 °C and comparison with previously tested Trosifol® BG-R-20.

Table 1. Summarized viscoelastic parameters investigated for Trosifol® Extra Strong

WLF model (reference temperature T_0 = 20 °C)			
C_1	18.4	C_2	75.6
Generalized Maxwell model			
G_∞ = 1.270 MPa			
τ_i [s]	G_i [MPa]	τ_i [s]	G_i [MPa]
1.000E-11	3.249E+02	3.039E+03	5.126E+00
5.298E-11	3.248E+02	1.610E+04	5.126E+00
2.807E-10	3.248E+02	8.532E+04	2.030E-01
1.487E-09	3.248E+02	4.520E+05	8.275E-02
7.880E-09	3.248E+02	2.395E+06	8.274E-02
4.175E-08	3.247E+02	1.269E+07	8.273E-02
2.212E-07	3.247E+02	6.723E+07	8.272E-02
1.172E-06	3.247E+02	3.562E+08	8.270E-02
6.210E-06	3.247E+02	1.887E+09	8.267E-02
3.290E-05	3.247E+02	1.000E+10	8.262E-02
1.743E-04	3.246E+02	1.425E+05	5.290E-06
9.237E-04	3.246E+02	4.924E+05	4.960E-06
4.894E-03	3.246E+02	1.701E+06	4.649E-06
2.593E-02	3.246E+02	5.878E+06	4.319E-06
1.374E-01	3.246E+02	2.031E+07	3.961E-06
7.279E-01	3.246E+02	7.017E+07	3.566E-06
3.857E+00	3.246E+02	2.424E+08	3.122E-06
2.043E+01	3.246E+02	8.377E+08	2.603E-06
1.083E+02	1.061E+02	2.894E+09	1.954E-06
5.736E+02	5.126E+00	1.000E+10	9.787E-07

5. COMPARISON WITH QUASI-STATIC LOADING AND DISCUSSION

To verify the response of the constructed model, its stress-strain response to the constant strain rate in tested temperatures was calculated and compared to the static shear tests of Trosifol® Extra Strong, which had been performed at Klokner Institute before [3].

Representative experimentally determined force-displacement diagrams at static loading at shear strain rates $\dot{\gamma}$ approximately equal to 0.0391; 0.0095 and 0.0024 s-1, and at the temperatures of 0; 20; 40 and 60 °C are presented in Fig. 7. The test arrangement was identical with DMTA except for the temperature sensors, which were not glued to the surface of the specimen, see Fig. 3c.

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The theoretical force-displacement relationships (Fig. 8) are given by the evaluated parameters of Maxwell model in Tab. 1 and Boltzmann's principle of superposition (1). After evaluating the integral (1) with the constant strain rate($\dot{\gamma}$), the shear response of Maxwell model in time is obtained as;

$$\tau(t,T) = \dot{\gamma}[G_{\infty}t + \alpha_T \sum_{i=1}^{n} G_i\, \tau_i (1 - \exp(-t/\alpha_T \tau_i)] \quad (5)$$

This comparison shows that the Maxwell model loaded with the certain strain rate at the certain temperature provides stiffer response than that experimentally measured in quasi-static tests. This may be caused by imperfections in strain rate, because its value was derived from the set displacement loading rate of frame 0.002, 0.008, and 0.032 mm/s and the mean value of interlayer thickness 0.845 mm, but real shear strain rate of loaded interlayer is lower due to the influence of the testing-frame stiffness. Another reason may be an imperfect temperature conditioning of the samples especially at 20 °C. In case of static tests, the temperature was not monitored by the sensor directly on the sample surface. The experimental temperature 20 °C was close to the ambient temperature (approx. 23 °C), thus that was difficult to ensure. Therefore, these are possible sources of errors.

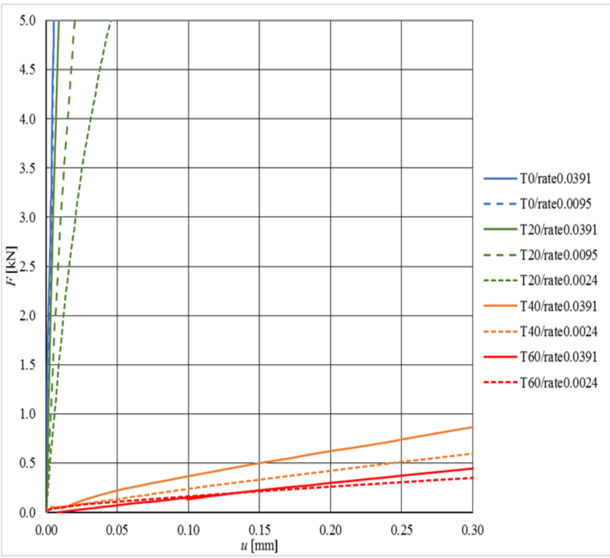

Figure 7. Force-displacement relationships determined experimentally by static loading with constant strain rate 0.0391; 0.0095 and 0.0024 s^{-1} at the temperature of 0; 20; 40 and 60 °C

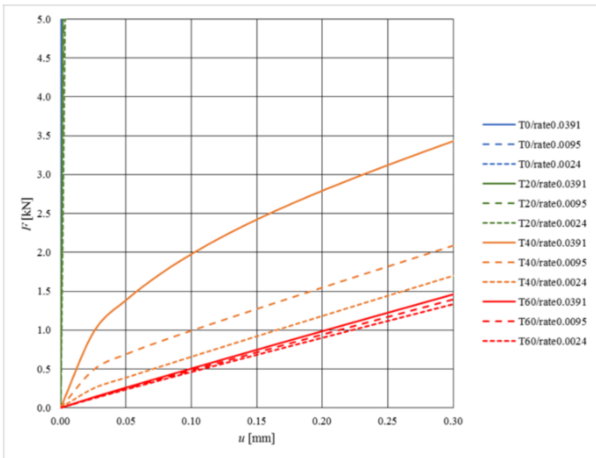

Figure 8. Theoretical force-displacement relationships determined from the evaluated generalized Maxwell model and WLF model, loading conditions correlate to the quasi-static tests.

6. CONCLUSION

The viscoelastic parameters and parameters of the WLF model of the polymeric interlayer Trosifol® Extra Strong for laminated glass were based on experimental DMTA method performed on single lap small scale glass specimens in shear. These parameters were further used to calculate the theoretical force-displacement diagrams, which were compared to the experimental diagrams obtained from quasi-static shear tests performed at the constant strain rates and temperatures. This comparison shows that the Maxwell model loaded with the certain constant strain rate at the temperature 20 °C, provides stiffer shear response of Trosifol® Extra Strong than that experimentally measured in static tests. This may be caused by inaccurate temperature measurements and conditioning of the specimen in case of quasi-static tests because the temperature of the specimen´s surface was not directly measured. For other tested temperatures (0, 40, and 60 °C), Maxwell and experimental force-displacement relations from static tests show better coincidence. To prove the reliability of the presented Maxwell model, sets of relaxation experiments at various temperatures in shear should be performed. This is another way how to get time-temperature performance of this widely used interlayer.

The viscoelastic properties of the Trosifol® Extra Strong polymer interlayer were also compared to the properties of Trosifol® BG-R-20 investigated previously. It is obvious that shear stiffness, resp. relaxation functions, vary greatly. Therefore, even when designing glass

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structures, it must be clearly established what type of interlayer is taken into account and the declaration of only the material base is not sufficient.

7. ACKNOWLEDGEMENT

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